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On theories of solar type III radio bursts

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In solar radiophysics, many theories for type III bursts have been proposed during the past 60 years. Almost all these theories are based on the plasma hypothesis, which assumes that (i) the radiation is mainly generated by Langmuir waves via nonlinear processes and (ii) the radiation has frequencies close to the local plasma frequency and/or its second harmonic in the source region. We feel strongly that it is time to advocate an alternative approach without recourse to the plasma hypothesis. This brief discussion explains why.

solar radiophysics, type III bursts, plasma hypothesis, electron cyclotron maser mechanism

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Several groundbreaking papers [1–3] reported surprising observational results in the field of solar radiophysics in 1950. These "seed" results and subsequent findings gave rise to a new branch of solar physics that is presently known as solar radiophysics. The rich scientific content and exciting research in solar radiophysics have been summarized in a number of monographs and review articles [4–9]. These works describe many fascinating and intriguing phenomena that portray the complexity of the subject, and most of the observations remain unexplained. There are a number of fundamental difficulties in explaining the phenomena. First, physical processes in the solar atmosphere cannot be directly measured through *in-situ* observations. As a result, discussions generally rely on inferences and hypotheses. Second, it often happens that theoretical explanations are not unique. Third, understanding induced radiation processes relevant to solar radiophysics is an immature topic in plasma physics. Fourth, there could be new plasma processes that are peculiar to the solar atmosphere but of which we have little knowledge. We hope that researchers will make breakthroughs that will explain the phenomena. What we need imminently are innovative ideas.

Most theories in solar radiophysics are concerned with type III bursts, which are considered later in this paper. Yet, for historical and traditional reasons, most of these discussions impose the plasma hypothesis, which is defined in the next section. The purpose of the present discussion is two-fold. First, we state that the plasma hypothesis is not proven, and second, we make general comments on existing theories.

The paper is organized as follows. Section 1 outlines the important observational results of type III radio bursts. Section 2 outlines the traditional approach in which enhanced Langmuir waves are thought to play deterministic roles. Motivated by an outstanding issue that was raised by observations made in the 1970s, we present a scenario of type III bursts that is based on a totally different notion in Section 3. Section 4 presents concluding remarks and a summary.

1 Introducing type III bursts and the plasma hypothesis

It is well known that the solar radio emission phenomenon comprises several major types of bursts and storms with different spectral characteristics. Among these, type III bursts are the best known for a number of reasons. First, the phenomenon occurs most frequently when the Sun is active. Second, among the several types of emissions, the type III

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emission is usually the most intense. Third, unlike the case for other types of emission, it has been well determined that the radiation in type III emission is associated with streaming energetic electrons created near the site of a solar flare.

In general, type III emission covers a broad range of wavelengths. Of particular interest is the meter-wavelength regime because the radiation associated with this regime is generated in the solar corona [1–3,10–12]. A comprehensive review of observations was presented by Suzuki and Dulk [12].

Among the many intriguing features of type III bursts, two have interested theorists the most. First, the radiation frequency seems to be dictated by the local plasma frequency in the source region, and second, dynamic spectra of the radiation show occasionally that the emission has two frequency bands. Since the ratio of the center frequencies of the bands is about 2, it is generally believed that the relation between the two waves is that they are fundamental (F) and harmonic (H) waves. It is generally assumed that the F and H waves have frequencies close to the local plasma frequency and its harmonic, respectively. A historical background of this hypothesis was presented by Wild [13].

Ginsburg and Zheleznyakov (G-Z) [14] proposed the first theory to address these issues in 1958. It was suggested by those authors that Langmuir waves excited by streaming electrons are responsible for the observed radiation via nonlinear processes. To explain F and H waves, G-Z theory suggests two processes: (i) Langmuir waves interacting with thermal protons leading to the generation of F waves and (ii) Langmuir waves interacting with Langmuir waves resulting in H waves. However, it was later realized by other theorists that G-Z theory has several theoretical difficulties when it is applied to type III burst observations, as discussed in a number of review articles (e.g. [6,8]). The proposed nonlinear processes are not sufficient to explain the observed brightness temperature. Moreover, in the low corona where the electron density gradient is steep, detuning of the wave-particle resonance becomes a difficult issue for the generation of F waves. Hence, in subsequent years, G-Z theory was refined and revised continually by many authors. Many interesting scenarios have been suggested along this line.

2 Key issues of concern and interest

Despite many sophisticated theories concerning type III bursts being published in the literature over the past half century, theorists need to be aware that most of these discussions are founded on two critical assumptions: (i) the observed radiation has frequencies close to the local plasma frequency and/or its second harmonic (i.e. the plasma hypothesis) and (ii) the ambient magnetic field is unimportant to the basic emission process. Obviously, if either of these assumptions turns out to be untrue, then almost all existing theories become inconsequential even if they produce quantitative results that seem to be in good agreement with observations. In the following, we comment on the two assumptions separately.

2.1 The plasma hypothesis

We have no doubt that the observed frequencies of type III radio bursts are close to the local plasma frequency. After all, it is a conclusion derived from extensive study and research conducted by many competent scientists (see reviews by Kundu [4] and Wild [13]). It has been shown that spatial variations in electron density in the corona determined from radio and other observations are consistent. This conclusion was further confirmed recently by the WAVES experiment aboard the Wind spacecraft [15].

However, from a theoretical viewpoint, it is entirely possible that the region where the wave is observed is not the true source region; i.e., the waves are generated elsewhere. In the true source region, the frequency of an emitted wave may not necessarily be the local plasma frequency. In fact, there is a highly interesting observational issue that unfortunately did not attract much attention at the time that it was reported. The issue is briefly described in the following.

As discussed above, type III bursts occasionally have two emission bands, namely the F and harmonic H waves; these waves have been observed to have frequency ratios close to 2 at a given time. All theories based on the plasma hypothesis assume that the H wave at a fixed frequency must be generated at a higher altitude while the F wave is produced at a lower altitude since the plasma frequency in the corona decreases monotonically with altitude. The simple picture is shown schematically in Figure 1. Nevertheless, a rather surprising result based on observational data was reported by several researchers [10,16–18]. It was found that at a

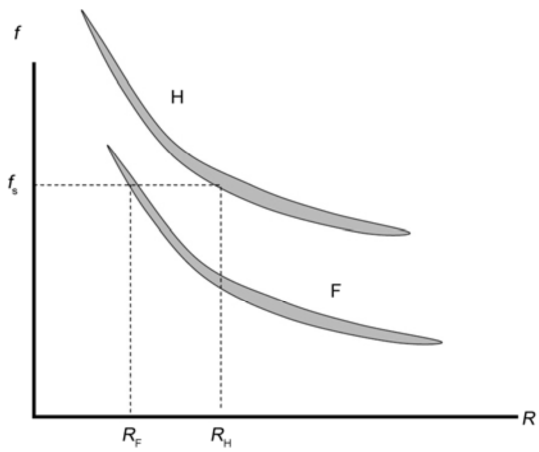

Figure 1 A schematic illustration of the dynamic spectra of type III bursts with F-H pair bands. According to theories based on the plasma hypothesis, one expects that for F and H waves with similar frequency, the H wave should have a source height R_H greater than the source height R_F of the F wave. However, observations found that these waves have overlapping source heights [10,16–18].

fixed frequency, the F and H waves have source regions that overlap. What does this mean? In an attempt to resolve the issue of overlapping source regions, two scenarios were proposed in the early years: one by Duncan [19] and the other by Robinson [20]. Both ideas grew from the fact that, in the solar corona, there are corrugated density structures (e.g. see Benz [21]) that imply the existence of under-dense and over-dense flux tubes. According to Duncan [19], the emission may occur inside an under-dense flux tube, where the density is at least four times lower than the exterior density, such that F and H waves with the same frequency would leave the duct at the same altitude, whereas Robinson [20] argued that over-dense density fibers could result in scattering that tends to shift the apparent source heights of both F and H waves. In short, both models are plausible but not satisfactory, and the problem is not fully explained.

Regardless of the physical origin of the issue of overlapping source regions, its implication is profound and far reaching. The crucial point is that the observational finding contradicts the physical picture derived from the plasma hypothesis. The issue emerged nearly 40 years ago but has not attracted much attention from theorists active in solar radiophysics

2.2 The effect of the ambient magnetic field is negligible

Most existing theories assume at the outset that the effect of the ambient magnetic field is unimportant and ignorable. This approximation may be justified if the discussion is restricted to (i) regions at sufficiently high altitudes where the background magnetic field is weak or (ii) the case in which the source of radiation is in the current-sheet region, where the local magnetic field is unimportant even if the altitude is low. The latter may occur as an isolated event from time to time as reported by Stewart and Labrum [22]. However, it is certainly not tenable for a general discussion. Another argument that may be given to justify the approximation is to presume that radiation is in the O mode only. The reason is that the dispersion relation is not sensitive to the electron gyro frequency, and in fact, the O-mode cutoff frequency happens to be the plasma frequency. However, this does not mean that the ambient magnetic field is always unimportant in the discussion of nonlinear processes. Moreover, excluding the X-mode *a priori* may not be a good approach to developing a theory that provides a general understanding of the observed phenomenon.

Another consideration, which is of great concern, is the high-frequency type III bursts generated at low altitudes near the flare site, where the ambient field is generally high. In the literature, it is considered that coronal type III bursts have frequencies ranging from several tens of megahertz to a few gigahertz. It is not clear whether the high-frequency type III bursts are still determined by the local plasma frequency. If they are, it is implied that the electrons in the low corona would have very high density, say 10^{10} per cm^3.

3 A scenario without recourse to the plasma hypothesis

Most existing theories of type III bursts (i) adopt the plasma hypothesis at the outset and then (ii) search for consistent nonlinear processes that give rise to the radiation of interest. The principal purpose is to show that the emissions of F/H bands are determined by the local plasma frequency and its second harmonic.

Motivated by the two critical issues discussed in the preceding section, a totally different scenario was proposed by Wu et al. [23,24] and Yoon et al. [25], in which the cyclotron maser mechanism [26,21] is advocated. The basic idea developed from observations that F/H waves with identical frequencies have overlapping source regions, as discussed previously in Section 2. In this more recent theory, we extend Duncan's notion by considering that, in the corona, there are density-depleted flux tubes in which the plasma density is much lower than the density of the exterior plasma (A model theory was proposed by Wu et al. [27] to explain the origin of such density depletion). Several essential points were considered by Wu et al. [23]: (i) waves emitted inside the duct have frequencies close to the local electron gyro frequency and/or second harmonic; (ii) the frequencies of the emitted waves are lower than the cutoff frequencies of the outside plasma so that the radiation cannot exit the duct; (iii) however, when an emitted wave propagates to a sufficiently high altitude where the cutoff frequency of the exterior plasma drops to a value lower than the wave frequency, it exits the duct and becomes visible; and (iv) it is therefore expected that waves having the same frequencies, regardless of where they are originated, exit at the same altitude. The basic physical picture is depicted in Figure 2, in which a model situation is shown and the physics is explained in the caption.

In the proposed scenario, the true source region is not observable because the emitted waves cannot leave the duct initially. It is considered that the emitted waves have frequencies close to the local electron gyro frequency and/or its second harmonic in the true source regions. However, when these waves exit at high altitudes, their frequencies are close to the local plasma frequencies in the observable source region (because of the effect of the cutoff frequency). Thus, it is clear that this theory yields results that are not only consistent with the "plasma hypothesis" but also explain the observations of source regions of F and H waves having identical frequency overlap. Yet, unlike the case for many existing theories in which the background magnetic field is ignored, the ambient field plays a key role in the emission process in the theory.

In principle, the theory emphasizes a generalized cyclotron maser process that leads to induced emission of radia-

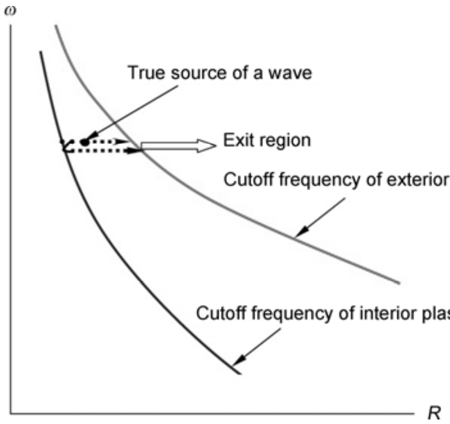

Figure 2 A schematic description of wave propagation in a density-depleted duct. A wave is emitted inside the duct, at the true source, but it cannot escape the duct regardless of its direction of propagation. As a result, the wave is not observable. If the wave propagates upward, it can exit the duct when it reaches at an altitude where the wave frequency exceeds the exterior cutoff frequency. A downward propagating wave is reflected when it reaches an altitude where the wave frequency is equal to the interior cutoff frequency.

tion. This may be discussed with linear kinetic theory. No sophisticated or inefficient nonlinear processes are needed. However, several more advanced issues need to be addressed: (i) quasilinear or nonlinear saturation of the radiation, (ii) the corresponding brightness temperature, and (iii) how the emission process is affected by intrinsic Alfvén waves in the solar plasma. Results relating to some of these issues will be reported soon.

4 Concluding remarks

Our opinion is that the issue arising from observations [10,16–18] that the F/H waves associated with type III radio bursts with equal frequencies have overlapping source regions has important and profound implications. The finding challenges the longstanding plasma hypothesis, which has been widely used by theorists during the past 60 years in solar radiophysics. Yet, the issue was ignored or overlooked by theorists active in the area of type III bursts.

It is certain that the observational finding does not support the picture that many theorists have conceived from the plasma hypothesis, as illustrated in Figure 1. We therefore believe that not only is an alternative scenario beyond the plasma hypothesis needed but also the alternative scenario must be able to resolve the issue of overlapping source regions. The cyclotron-maser scenario by Wu et al. [23] is motivated by these considerations. Here we summarize the merits of the proposed scenario.

(i) The theory does not use the plasma hypothesis.

(ii) For the first time, the theory introduces the concept of a true source region and an observed source region.

(iii) The emission process leads to direct amplification of radiation and no *ad hoc* nonlinear processes are imposed.

(iv) The scenario naturally explains the issue of overlapping source regions discussed in Section 3.

Indeed there are many intriguing and fascinating phenomena other than type III bursts. Such phenomena may appear mysterious now but their actual physics might not be particularly sophisticated. Perhaps all solar radio emissions are attributed to some fundamental but simple emission mechanism that we do not yet know of. Owing to different magnetic field configurations, the velocity distribution of energetic electrons and other basic parameters, the spectral characteristics of the resultant radiation become very different in various spatial regions and time intervals. Theorists are encouraged to take a broader look at solar radiophysics and not limit their interest to type III bursts.

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